Discrete Yttrium(III) Complexes as Lactide Polymerization Catalysts

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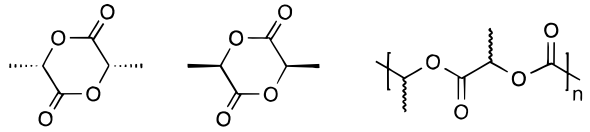
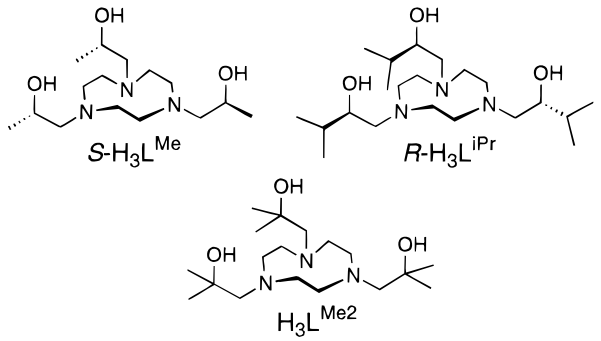
Received January 5, 1999

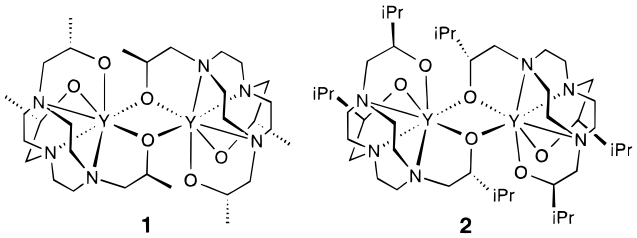
The development of biodegradable polymers derived from renewable resources offers solutions to problems associated with traditional commodity plastics ranging from waste management to dwindling petrochemical feedstocks. Important targets include polyesters derived from the ring-opening polymerization of cyclic esters. Polylactide (PLA) is a notable example with numerous biomedical and pharmaceutical applications.[1] A goal of



current research is to design new catalyst systems with discrete ligand environments that are amenable to systematic variation, thus enabling the rational control of PLA molecular and physical properties.[2] Simple lanthanide compounds with multiple monodentate ligands (e.g., alkoxides) have been found to be particularly efficient catalysts for the synthesis of high-molecular-weight PLA from lactide,[3] but judicious control of their reactivity has been difficult due to a lack of knowledge of precatalyst structure and/or an inability to systematically vary catalyst structure through ligand design. We report the synthesis and full characterization of novel yttrium complexes ligated to the multidentate ligands *S*-H_3L^{Me},[4] *R*-H_3L^{iPr},[5] and H_3L^{Me2},[6] representatives of a potentially larger class of similar ligands with substituents of variable size and shape.[7] Preliminary studies show that these new, well-defined complexes catalyze the polymerization of lactide and that structural differences influence the polymerization rate and the polymer molecular weights.



The dinuclear complexes **1** and **2** were isolated as colorless crystalline solids in 52 and 65% yields, respectively, by treating the appropriate ligand with $Y[N(TMS)_2]_3$ in toluene at ambient temperature followed by crystallization.[8,9] X-ray diffraction analyses revealed similar dinuclear structures for the two complexes.[10] Each yttrium is ligated by three macrocyclic nitrogen donors, two terminal η^1-alkoxides, and two bridging η^2-alkoxides; each ligand contributes five donors to one metal ion, with the sixth bridging. The structures illustrate novel coordination modes for their respective ligands. Thus, sterically hindered *R*-L^{iPr} has only been observed to form monomeric complexes with a range of metals,[5] and although dimeric complexes of *S*-L^{Me} with various transition metal ions are known, they are of the general form $[M(S\text{-}L^{Me}\cdot S\text{-}H_3L^{Me})M]^{n+}$ (e.g., M = Co^{III} or Cr^{III}, $n = 3$) in which hydrogen bonds join the dimeric halves comprising the ligand that is deprotonated on one side and protonated on the other.[11] The ^1H NMR spectra of **1** and **2** in CD_2Cl_2 are sharp and support retention of their dimeric, C_2-symmetric structures in solution.



Complexes **1** and **2** are active lactide polymerization catalysts (Table 1). Modest polymerization rates at relatively low [M]/[Y] ratios (M = monomer; Y = yttrium center) were observed with complex **1**, but the product polymers were relatively monodisperse (entries 1 and 2).[12] Increases in the [M]/[Y] ratio led to slower polymerizations and similar molecular weight distributions (entries 3−5). However, we did not observe control of the polymer molecular weight with changes in the [M]/[Y] ratio.[13]

Complex **2** exhibited dramatically different behavior. The polymerization rates were significantly faster at identical [M]/[Y] ratios as compared to complex **1** (entries 2 and 7; entries 5 and 8). Molecular weights of the polymers prepared using **2** were generally 2−3 times greater than the polymers obtained using **1**. Although

Table 1. Polymerization of D,L-Lactide in CH_2Cl_2 at 25 °C[a]

entry	no.	[M]/[Y]	time (h)	yield (%)	M_n ($\times 10^3$)	M_w/M_n
1	**1**	50	2	62	19.8	1.30
2	**1**	150	2	31	17.0	1.26
3	**1**	150	24	64	18.4	1.31
4	**1**	150	48	88	20.9	1.31
5	**1**	450	24	62	8.6	1.25
6	**2**	50	2	100	35.9	2.20
7	**2**[b]	150	0.5	97	52.7	1.55
8	**2**	450	24	98	62.5	2.13
9	**2**[b]	1000	0.5	11	7.7	1.39
10	**2**[b]	1000	2	25	20.2	1.29
11	**2**[b]	1000	96	66	32.3	1.77
12	**3**	150	0.03	90	66.9	1.62
13	**3**	450	0.17	81	94.6	1.26
14	**3**[b]	1000	0.5	66	45.7	1.55

[a] For details on the polymerization procedure, see the supporting information. [b] Aliquots removed at the indicated time interval.

10.1021/ma990005k CCC: $18.00
Published on Web 03/19/1999

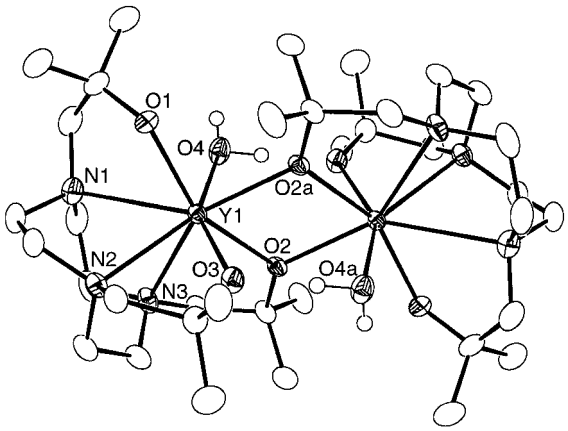


Figure 1. Representation of the X-ray structure of **3** as 50% ellipsoids. All hydrogen atoms except those on the coordinated H_2O are omitted for clarity. Selected interatomic distances (Å): Y(1)−O(1), 2.200(2); Y(1)−O(3), 2.258(2); Y(1)−O(2a), 2.323(1); Y(1)−O(2), 2.325(2); Y(1)−O(4), 2.453(2); Y(1)−N(2), 2.662(2); Y(1)−N(3), 2.664(2); Y(1)−N(1), 2.810(2); Y(1)···Y(1a), 3.7555(4).

molecular weight distributions were generally higher for the polymers produced by **2**, some control over molecular weight was observed using various [M]/[Y] ratios at fixed yield (entries 6−8). In addition, the sampling of one reaction mixture at [M]/[Y] = 1000 showed a roughly linear increase in molecular weight with increasing yield (entries 9−11). While NMR analysis[14] indicated no stereoelectivity in the polymerizations initiated by enantiopure **1** and **2**, polymerization of pure L-lactide using **2** as catalyst ([M]/[Y] = 150; 24 h) gave pure isotactic PLA. Thus, no epimerization of lactide or PLA occurs, arguing against an anionic polymerization mechanism and boding well for future extension of this work aimed at developing stereoelective catalysts. Overall, from these initial investigations it is clear that **1** and **2** are active polymerization catalysts and that modest changes in the ligand structure can have significant effects on the polymerization activity.

Encouraged by the polymerization activity of **1** and **2**, we prepared an additional variant, **3**, with ligand L^{Me2}. An X-ray crystal structure of **3** (Figure 1) indicated a dinuclear topology akin to those of **1** and **2**, except each Y(III) ion is 8-coordinate with a coordinated water molecule that is H-bonded to an alkoxide oxygen [O(3)···O(4a) = 2.571(2) Å]. In solution, **3** exhibited a sharp ^{1}H NMR spectrum at −40 °C like the ambient temperature spectra of **1** and **2**, but the peaks broadened reversibly upon warming, indicating fluxional behavior. In addition to these solid state and solution structural differences, PLA production using **3** was much faster than the reactions promoted by complexes **1** and **2** at identical catalyst loadings (compare entries 9, 11, and 14). The presence of coordinated water[15] and/or the highly fluxional solution behavior of **3** are possible factors responsible for its high activity.

In conclusion, we have discovered a set of novel yttrium complexes that display unprecedented coordination geometries for the ligands *S*-H_3L^{Me}, *R*-H_3L^{iPr}, and H_3L^{Me}. These complexes are promising catalysts for the ring-opening polymerization of lactide. The demonstration of readily manipulated ligand effects on polymerization reactivity in these discrete, well-characterized complexes represents an important step in the development of highly selective lanthanide catalysts for the controlled synthesis of PLA and other polyesters.

Acknowledgment. This work was supported by the National Science Foundation (CHE-9207152 and a National Young Investigator Award to W.B.T.) and by the Institute of Technology and the Department of Chemistry at the University of Minnesota. We thank JennySue Abbott for valuable technical assistance with the GPC measurements.

Supporting Information Available: Text giving synthetic procedures and characterization data for all compounds and full descriptions of the X-ray crystal structure determinations, tables of crystal structure data, atomic coordinates, bond distances and angles, anisotropic thermal parameters, torsion angles, and hydrogen atom parameters, and figures showing the structures and unit cells of **1**−**3**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(8) Synthetic procedures and characterization data for all compounds are provided in the Supporting Information.

(9) An alternative synthetic route involved refluxing *S*-H_3L^{Me} with $Y(O_3SCF_3)_3$ in CH_3CN (18 h) followed by volume reduction and vapor diffusion of Et_2O. The product was formulated as $[(S\text{-}H_3L^{Me})Y(CH_3CN)(O_3SCF_3)](O_3SCF_3)_2$ on the basis of CHN analysis, FAB−MS, ^{1}H NMR, FTIR, and X-ray diffraction data which showed ligation of *S*-H_3L^{Me} to the Y(III) ion. This complex was inactive for the polymerization of lactide. Deprotonation of by NEt_3 induced dimerization to yield **1** (^{1}H NMR).

(10) X-ray data for **1** ($C_{30}H_{60}N_6O_6Y_2$, MW = 778.86): monoclinic, space group $P2_1$, a = 14.0455(3) Å, b = 13.8796(3) Å, c = 20.1374(3) Å, β = 100.597(1)°, V = 3858.8(1) Å^3, Z = 8. X-ray data for **2** ($C_{42}H_{84}N_6O_6Y_2$, MW = 946.97): triclinic, space group $P\bar{1}$, a = 11.2760(1) Å, b = 11.3444(2) Å, c = 24.1959(4) Å, α = 78.085(1)°, β = 89.051(1)°, γ = 82.199(1)°, V = 3000.21(7) Å^3, Z = 2. X-ray data for **3** ($C_{43}H_{84}N_6O_8Y_2$, MW = 990.98): triclinic, space group $P\bar{1}$, a = 10.0894(3) Å, b = 10.9681(3) Å, c = 12.4550(4) Å, α = 84.022(1)°, β = 83.067(1)°, γ = 63.293(1)°, V = 1220.31(6) Å^3, Z = 1. For further details, see the Supporting Information.

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(12) Some of the GPC traces were bimodal. This is presumably a result of efficient transesterification in competition with ring-opening polymerization. See: Baran, J.; Duda, A.; Kowlaski, A.; Szymanski, R.; Penczek, S. *Macromol. Rapid Commun.* **1997**, *18*, 325−333.

(13) The initiation may occur through insertion of an alkoxide from the ligand into lactide, but experimental evidence is lacking. Although variable initiator efficiency may be responsible for the inability to systematically control molecular weight in polymerizations with **1** and **2**, further studies (including absolute molecular weight determinations) will be necessary before the initiator efficiency can be adequately defined.

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(15) So far, attempts to assess the effect of the coordinated water by stirring solutions of **3** with molecular sieves or heating the solid under vacuum (90 °C, 8 h, 0.1 Torr) have failed to remove the aquo ligand.

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